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Assessment and Analysis of Water Environmental Risk Using Pressure-state-response Model in Ningbo, China

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Water resources are an important guarantee for human life, and the health of the water environment directly affects socioeconomic development. With the rapid development of urbanization and industrialization, wastewater has a huge impact on the water environment. The assessment of water environmental risk has become an important measure for long-term sustainable development. In this study, we proposed a framework based on the pressure-state-response (PSR) model to assess and analyze the changing tendencies of the water environment carrying capacity (WECC). The results showed that WECC increased from 2011 to 2017 and the evaluation status changed from very unhealthy (V) to basically healthy (II). Compared with the carrying capacity of each indicator, the most influential factors were the amount of chemical oxygen demand (COD) discharged, water consumption per capita, industrial water consumption increment per 10^4-yuan, greenbelt area per capita, the wastewater processing capacity of industrial facilities, and the amount of industrial wastewater. This study concisely shows the status of the water environment in Ningbo and accurately identifies the key problems of water quality. The assessment and analysis of water environmental risk can be a scientific and effective reference for social development planning. By decreasing the amount of wastewater and improving the water quality, WECC can be kept under control for a long time.

1. Introduction

With the development of urbanization and industrialization, natural resources have been rapidly consumed, which have led to the risks of overexploitation of resources and environmental pollution. Water is one of the most important natural resources; thus, water environmental risk has restricted socioeconomic sustainable development because of industrial wastewater, urban sewage, pesticide residues, and so forth.(1) Water pollution has become an increasingly serious social disaster owing to urban population explosion and industrial discharge.(2–5) Although the natural ecosystem can self-repair with little risk, there is a threshold limitation such that water environmental risk has a bottleneck that restricts socioeconomic development.(6)

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The theory of carrying capacity evolved from ecological studies that describe the maximization of population growth.(7) With the expansion of research fields, some experts applied it to resources, environment, land, population, and others.(8–11) The water environment carrying capacity (WECC) reflects the relationship between socioeconomic development and water environmental coordination, which was an important reference to formulate the development planning of water environmental protection, water resource regulation, and human activities.(12,13) The connotation of WECC included the maximum capacity to support socioeconomic development, the maximum volume to absorb water pollution, and the sustainable economic, social, and ecological development scales.(14) On the basis of an effective screening of WECC in the China National Knowledge Infrastructure (CNKI) and Web of Science (WOS), most quantitative studies were conducted by Chinese scholars, and foreign research studies and their applications were relatively few.(15) In 2020, the evaluation method for WECC was issued by the Ministry of Ecology and Environment of China (http://www.mee.gov.cn/xxgk2018/xxgk/xxgk06/202010/t20201022_804390.html). The evaluation result and changing tendency can support the water environmental protection planning of some key basins in China.

In existing research, the evaluation method of WECC mainly focused on the vector modular,(16) fuzzy comprehensive evaluation,(17) artificial neural network,(18) analytic hierarchy process (AHP),(19) system dynamics (SD),(20) and so forth. The vector modular is the simplest one, but the accuracy of its result is always low. On the basis of the fuzzy relationship matrix, the fuzzy comprehensive evaluation is used to judge the WECC grade according to the principle of maximum subjection; however, some indicators' effective information is often lost. The artificial neural network and SD model can deal with the complex changing process of WECC; in contrast, the construction of the component modeling and training sample library is complicated. From the multi-indicator framework, AHP is a flexible and concise method of evaluating WECC, but the result will be affected by subjective judgement. The pressure-state-response (PSR)(21) model defines the relationship of each subsystem in the whole natural ecosystem and has been extended to driving-force-pressure-state-impact-response (DPSIR),(22) driving-force-pressure-state-impact-response-management (DPSIRM),(23) and driving-force-pressure-state-response-control (DPSRC) models.(24) We have evaluated the integrated capacity of eight coastal cities in the Yangtze River area and predicated the changing tendency of the feature. However, it is a macroscopic conclusion, which refers to the comprehensive carrying capacity of a natural ecosystem and cannot reflect the key restricted factor. For long-term sustainable development, the carrying capacity evaluation of an individual ecosystem is also an important research area.

In this paper, we propose an approach using the WECC evaluation model based on the PSR framework. By combining subjective analysis and objective calculation, the indicator's weight was calculated on the basis of the entropy theory, and the carrying capacity was assessed on the basis of the state space model. Taking Ningbo as the research object, we assessed WECC from 2011 to 2017. This approach can be used to assess the WECC status and analyze the changing rule to discover the key factors that affect the water environment health.

2. Study Area and Data

Ningbo is located in the east of Zhejiang Province (Fig. 1). In the China import and export trade, it is an important industrial and economic center, especially in the integrated development of the Yangtze River Delta.(25) With the expansion of the economic scale and development model, water pollution is gradually worsening because of manufacturing and chemical industries. In 2018, the wastewater discharge was 785 million tons, but the industrial wastewater discharge accounted for 151 million tons, which was higher than in most big cities.

In our previous studies, we proposed the indicator system based on the DPSRC framework and validated its feasibility.(26,27) To analyze the signal carrying capacity, we simplified the indicator system on the basis of the PSR framework (Fig. 2). This framework is divided into three dimensionalities of pressure (P), state (S), and response (R). Rainfall, groundwater, and surface runoff are the main sources of regional water resources, which support the demands of people and industrial development. Wastewater discharge and consumption are the main pressures on the water environment. With surges in population and energy consumption, the water environment cannot support socioeconomic development. By improving governance measures and increasing the budget for investments, the water quality can return to a relatively healthy state.

On the basis of this framework, the evaluation index system was constructed with some representative indicator. With result comparability, data availability, and quantification, the screened index system was proposed, including 22 indicators in three dimensions (Table 1). Most indicators' data was obtained from the Ningbo Statistical Yearbook (http://tjj.ningbo.gov.cn/col/col1229041012/index.html; accessed on 20 Aug. 2022), Ningbo Water Resources Bulletin (http://slj.ningbo.gov.cn/col/col1229051287/index.html; accessed on 20 Aug. 2022), and Zhejiang

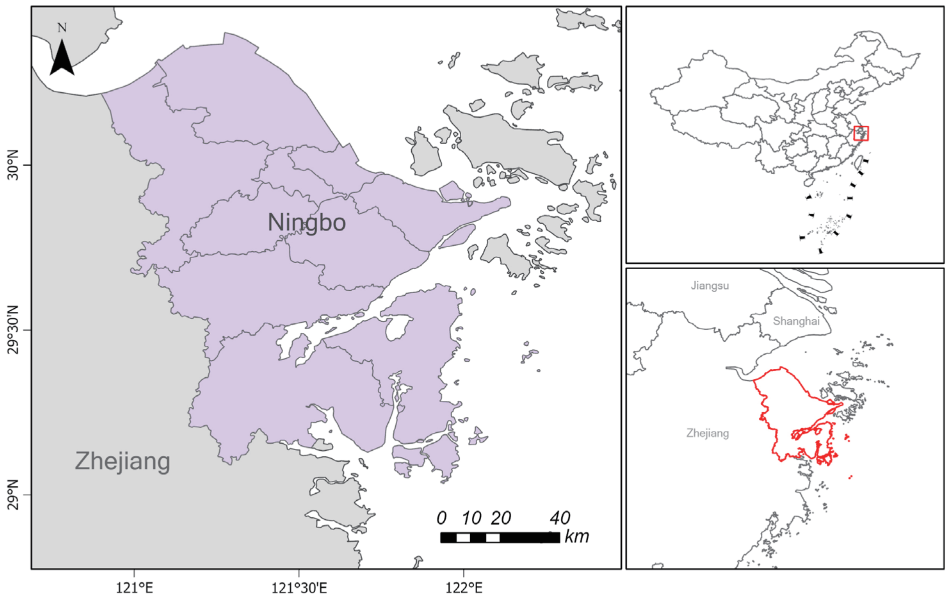


Fig. 1. (Color online) Thematic map of study area.

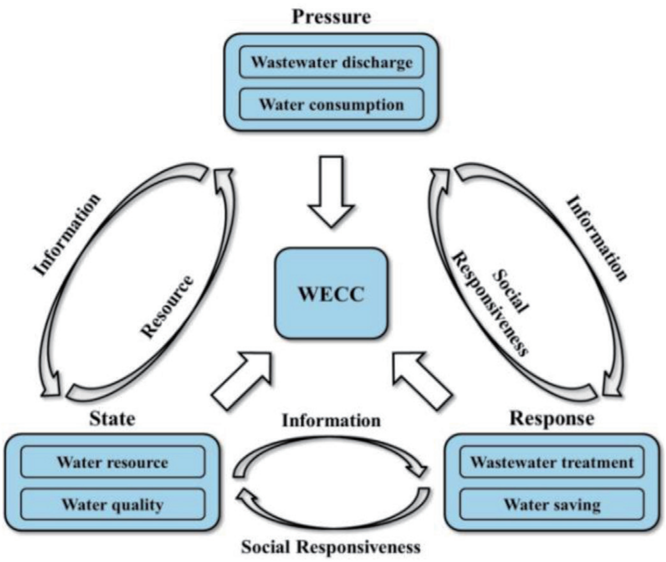


Fig. 2. (Color online) Construction of PSR framework.

Table 1
Evaluation index system of WECC.

Subsystem	Indicator	Attribute
P	Population density	Negative
	GDP per capita	Positive
	Energy consumption per unit GDP	Negative
	Wastewater discharge	Negative
	COD discharge	Negative
	Water consumption per capita	Negative
	Water consumption per 10^4-yuan	Negative
	Water consumption of industrial output per 10^4-yuan	Negative
S	Water resources per capita	Positive
	Precipitation	Positive
	Groundwater resources	Positive
	Total water supply	Positive
	Water quality compliance rate	Positive
	Proportion of water quality above class II	Positive
	Green area per capita	Positive
R	Amount of water conserved	Positive
	Investment on environmental pollution protection	Positive
	Centralized wastewater treatment volume	Positive
	Centralized COD treatment volume	Positive
	Processing capacity of industrial wastewater treatment facilities	Positive
	Industrial wastewater treatment volume	Positive
	Proportion of centralized treatment in sewage plant	Positive

Natural Resources and Environment Statistical Yearbook (http://tjj.zj.gov.cn/col/col1525563/index.html; accessed on 20 Aug. 2022). On the basis of the correlation analysis and linear tendency, the data error and extreme value corrections were carried out. With the development of the social economy and the change in data statistical caliber, some indicators have been replaced or deleted. Considering the comparability of the evaluation result, the 2011 to 2017 data of each indicator were used in this study.

3. Methodology

3.1 Data normalization

Because the indicator data, which is a quantitative number with a clear unit, comes from the Statistical Yearbook, it cannot be calculated before standardization. There are some common methods of normalizing the indicator data, including the use of the maximal/minimal value, z-score, and logistics model, and decimal calibration. In this study, the index system is divided into two categories, namely, positive and negative indicators. The data normalization method is proposed by using the maximal/minimal value model, but the result is affected by the zero value after indicator normalization, which has been validated in our previous study.(26) Through an adjustment coefficient, the normalization formula is as follows:

Negative indicator:

$$Y_{ij} = \left(1 - K\right) + K \times \frac{Y^0_{jmax} - Y^0_{ij}}{Y^0_{jmax} - Y^0_{jmin}}, \tag{1}$$

Positive indicator:

$$Y_{ij} = \left(1 - K\right) + K \times \frac{Y^0_{ij} - Y^0_{jmin}}{Y^0_{jmax} - Y^0_{jmin}}, \tag{2}$$

where Y_{ij} is the indicator normalized value, Y^0_{ij} is the indicator original value, Y^0_{jmax} is the maximum value of all indicators, and Y^0_{jmin} is the minimum one. K is an adjustment coefficient, which is defined as 0.9 in this study.

3.2 Indicator weight

The weight refers to an importance order of each indicator. In the multi-indicator evaluation model, we have proposed a weight calculation method based on the entropy theory,(26) which is a thermodynamics concept that reflects the material's state information. In this paper, the formula is

$$b_{ij} = \frac{Y_{ij}}{\sum_{i=1}^{n} Y_{ij}}, \tag{3}$$

where b_{ij} is the proportion of each indicator's characteristic.

$$H_j = -\frac{1}{\ln n}\sum_{i=1}^{n} b_{ij} \ln b_{ij} \tag{4}$$

$$\omega_j = \frac{1 - H_j}{m - \sum_{j=1}^{m} H_j} \tag{5}$$

Here, w_j is the indicator weight, H_j is the information entropy, m is the total number of evaluation years, and n is the total number of evaluation indicators. In particular, $0 \le \omega_j \le 1$, $(j = 1, 2...n)$, $\sum_{j=1}^{n} \omega_j = 1$.

3.3 WECC calculation

The space-state model reflects the best status of the evaluation object in three dimensions based on the Euclidean geometry distance. We validated it in our previous studies.(24,26,27) From the indicator normalized value, the evaluation matrix is

$$D = \begin{matrix} d_{12} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{matrix} = \begin{matrix} \omega_1 Y_{12} & \omega_1 Y_2 & \cdots & \omega_1 Y_{1n} \\ \omega_2 Y_{11} & \omega_2 Y_{12} & \cdots & \omega_2 Y_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \omega_m Y_{m1} & \omega_m Y_{m2} & \cdots & \omega_m Y_{mn} \end{matrix}. \tag{6}$$

The carrying capacity formula of each indicator is

$$C_i = \sum_{j=1}^{n} \omega_j \times Y_{ij}\ , \tag{7}$$

where C_I is the evaluation result of the i indicator, Y_{ij} is the normalized value of each indicator, m is the total number of indicators, and n is the total number of evaluation years.

From the PSR evaluation model, the WECC evaluation formula is

$$WECC = \sum_{k=1}^{3} \omega_k \times C_i\ , \tag{8}$$

where ω_k is the weight of each evaluation subsystem. In this study, the subsystem weight was calculated using the AHP model.

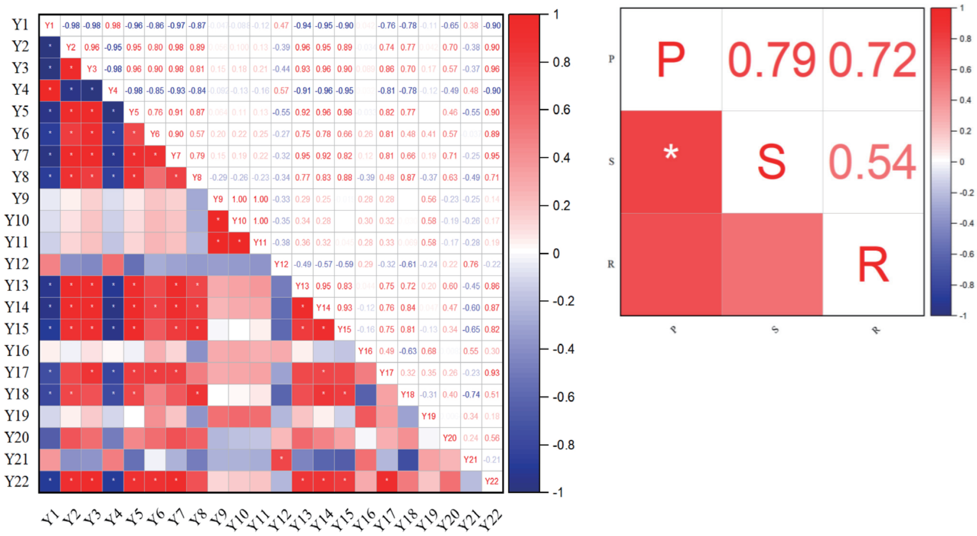
4. Results and Analysis

4.1 Evaluation data contrast

The results of data normalization and indicator weight are shown in Table 2. The correlations and heatmap of each indicator were calculated using the Origin Pro software (Fig. 3).

Table 2
Normalized value and weight of each indicator.

Subsystem	ω_k	Indicator	2011	2012	2013	2014	2015	2016	2017	ω_i
P	0.389	Y_1	1.0000	0.9571	0.8714	0.6571	0.5286	0.3571	0.1000	0.0315
		Y_2	0.1000	0.2373	0.3831	0.4792	0.5608	0.7294	1.0000	0.0372
		Y_3	0.1000	0.2379	0.2724	0.5727	0.6335	0.9338	1.0000	0.0441
		Y_4	1.0000	0.9649	0.9718	0.7196	0.5622	0.1982	0.1000	0.0397
		Y_5	0.1000	0.1801	0.2847	0.3413	0.4639	0.9458	1.0000	0.0541
		Y_6	0.1419	0.2186	0.1000	0.9651	0.9512	0.9930	1.0000	0.0576
		Y_7	0.1000	0.2800	0.4000	0.6400	0.7000	0.8200	1.0000	0.0347
		Y_8	0.1614	0.1000	0.2636	0.3045	0.1818	0.5091	1.0000	0.0604
S	0.308	Y_9	0.1000	1.0000	0.3562	0.3967	0.9112	0.7065	0.3276	0.0388
		Y_{10}	0.1000	1.0000	0.3966	0.3953	0.9675	0.7489	0.3654	0.0375
		Y_{11}	0.1000	1.0000	0.3777	0.3968	0.9713	0.7511	0.3968	0.0372
		Y_{12}	0.3774	0.4045	0.7801	1.0000	0.2184	0.1000	0.1914	0.0525
		Y_{13}	0.1000	0.3989	0.4838	0.4396	0.7385	0.8234	1.0000	0.0309
		Y_{14}	0.1000	0.4000	0.2500	0.4000	0.5500	0.8500	1.0000	0.0398
		Y_{15}	0.1000	0.1243	0.1521	0.2077	0.2425	0.9548	1.0000	0.0863
R	0.302	Y_{16}	0.3719	0.3719	0.8899	0.9482	1.0000	1.0000	0.1000	0.0363
		Y_{17}	0.1000	0.2374	0.3381	0.5568	0.5445	1.0000	0.5574	0.0369
		Y_{18}	0.2213	0.3901	0.1000	0.1688	0.2925	0.4679	1.0000	0.0530
		Y_{19}	0.2579	0.2579	0.2549	0.3816	1.0000	0.5070	0.1000	0.0468
		Y_{20}	0.1000	0.1103	0.5766	0.7657	0.6334	0.2227	1.0000	0.0545
		Y_{21}	0.5538	0.1806	0.6727	1.0000	0.7052	0.1348	0.1000	0.0546
		Y_{22}	0.1000	0.2672	0.4228	0.7425	0.6126	1.0000	0.8857	0.0359



(a) (b)

Fig. 3. (Color online) Heatmap of indicator's weight.

In Fig. 3(a), the red block represents the greater indicator's correlation and the blue block is relatively small. The population density and wastewater discharge are negatively correlated with others, which is not conducive to the healthy development of the water environment. The positively correlated indicator includes GDP per capita, energy consumption per unit GDP, COD discharge, water quality compliance rate, the proportion of water quality above class II, and the proportion of centralized treatment in a sewage plant. Improving the water quality control strength and increasing the vegetation area are beneficial to the WERR balance. The heatmap of the three subsystems shows that they are all positively correlated, and the highest correlation is between the pressure subsystem and the state subsystem [Fig. 3(b)].

From the weight calculation model, the top six indicators are green area per capita, the water consumption of industrial output per 10^4-yuan, water consumption per capita, industrial wastewater treatment volume, the processing capacity of industrial wastewater treatment facilities, and COD discharge. The weights of the pressure, state, and response subsystems are 0.389, 0.308, and 0.302, respectively, which show that environmental pressure is the key factor affecting the water resource health.

4.2 WECC assessment

An equal grading method was adopted to construct the evaluation criterion to measure the state of the water environment. The critical values of grades I, II, III, IV, and V were 0.25, 0.20, 0.15, 0.10, and 0.00, respectively. When it fell within the range of (∞, 0.25), WECC was defined as grade I (very healthy). When it was within the range of (0.25, 0.20), WECC was defined as grade II (basically healthy). At values within the range of (0.20, 0.15), WECC was defined as grade III (healthy), and at values within the range of (0.15, 0.10), WECC was defined as grade IV (unhealthy). At values within the range of (0.10, 0.05), WECC was defined as grade V (very unhealthy).

The changing trends of WECC are shown in Fig. 4. The WECC of Ningbo showed a general growth from 2011 to 2017 (from 0.0800 to 0.2315). The evaluation grade changed from grade V to grade II, reflecting improvements in the water environment. The growth of WECC slowed down gradually, and WECC would be close to the maximum under the current conditions. Therefore, there is still a long way to improve the WECC of Ningbo.

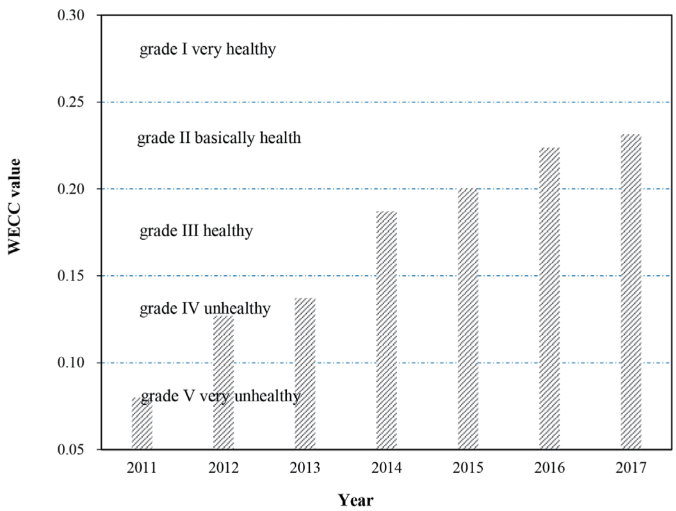


Fig. 4. (Color online) Changing trends of WECC from 2011 to 2017.

4.3 Analysis of key factors

In the pressure subsystem, except for population density (Y_1) and wastewater discharge (Y_4), all indices showed a general growth trend [Fig. 5(a)]. The improvement of each indicator in the pressure subsystem resulted in higher WECC in Ningbo. Water consumption per capita (Y_6) increased significantly from 2013 to 2014, which indicated that water consumption was the most important factor for the pressure subsystem.

In the state subsystem, water resources per capita (Y_9) and the trends of precipitation (Y_{10}) and groundwater resources (Y_{11}) were consistent with the carrying capacities of the state subsystem from 2012 to 2013 and from 2016 to 2017 [Fig. 5(b)]. The results reflected that Y_9, Y_{10}, and Y_{11} were the main factors restricting the state subsystem. Water quality compliance rate (Y_{13}), the proportion of water quality above class II (Y_{14}), and green area per capita (Y_{15}) were increased in general from 2011 to 2017, indicating that Y_{13}, Y_{14}, and Y_{15} were the major factors for the carrying capacity value of the state subsystem growth, and water quality was the most important factor of the state subsystem.

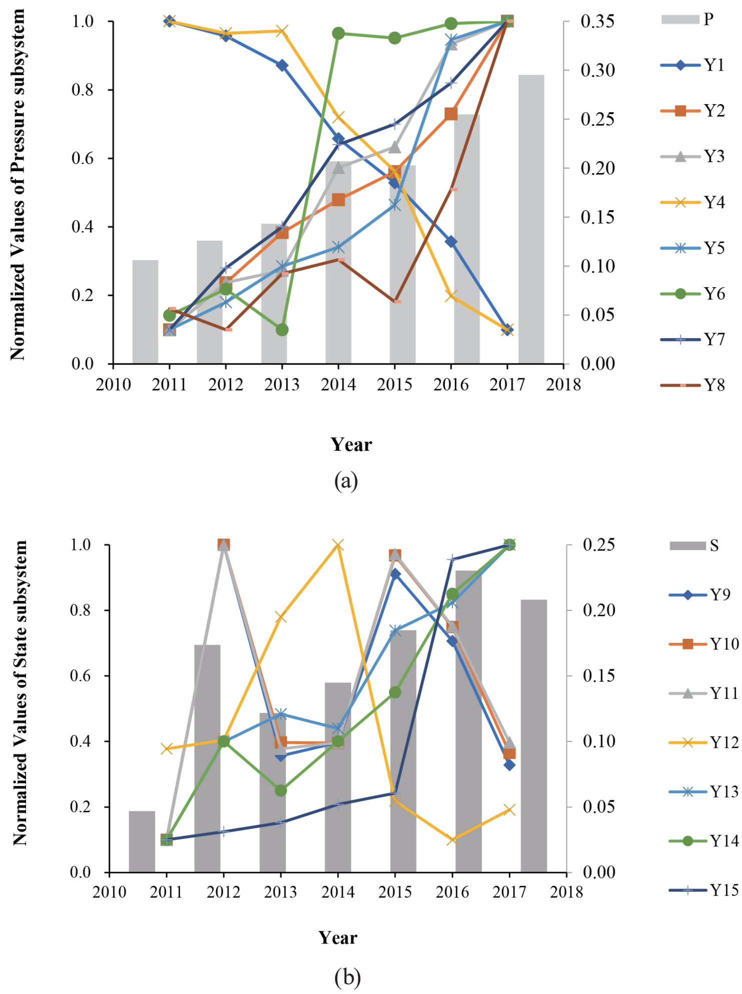
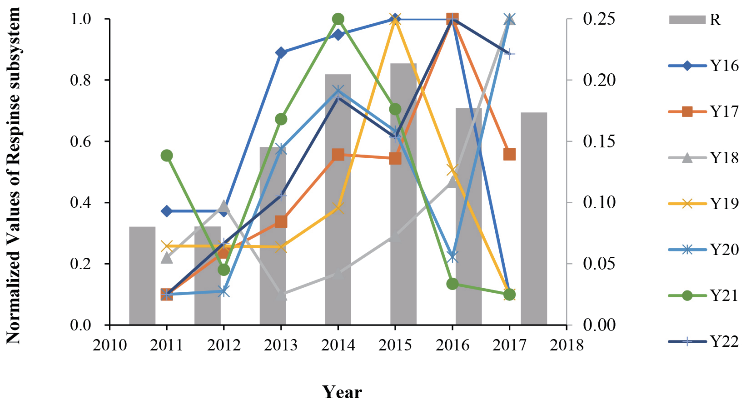


Fig. 5. (Color online) Normalized values of each indicator.



(c)

Fig. 5. (Continued) (Color online) Normalized values of each indicator.

In the response subsystem, we found that all indices showed a fluctuating trend [Fig. 5(c)]. The centralized COD treatment volume (Y_{19}), the processing capacity of industrial wastewater treatment facilities (Y_{20}), and industrial wastewater treatment volume (Y_{21}) decreased significantly from 2015 to 2016, which indicated that these indices may be the key factors leading to the carrying capacity decline of the subsystem from 2015 to 2016. To summarize, the decrease in water consumption and the improvement of the water quality have shown great effects, which were the key factors that promoted the increase in WECC.

The changing trends of the carrying capacity of each subsystem are shown in Fig. 6. The carrying capacity of each subsystem presented a different degree of growth. Compared with the carrying capacity in 2011, the values for 2017 in terms of pressure, state, and response increased by 0.1891, 0.1613, and 0.0933, respectively. The added value of the pressure subsystem was the largest, reflecting that pressure was the most important factor affecting WECC. The increase in WECC was largely attributed to the improvement of the carrying capacity of the pressure subsystem.

5. Discussion

In our study, we constructed an evaluation system based on water environment pressure, water eco-environmental state, and environmental protection response. Among them, the environmental protection response was a forward factor of WECC, the water environmental state was the basic factor, and the water environment pressure was the inhibitory factor. All factors interrelate and affect each other. The proposed PSR framework model provided a new method to construct the WECC evaluation index system dynamically.

Ningbo's WECC showed a general growth from 2011 to 2017 (from 0.0800 to 0.2315), and the evaluation grade changed from grade V to grade II, reflecting improvements in the water environment. On a temporal scale, the PSR model reflected the dynamic changes in WECC and the impact factors in Ningbo over the past seven years. These changes contributed to a deeper

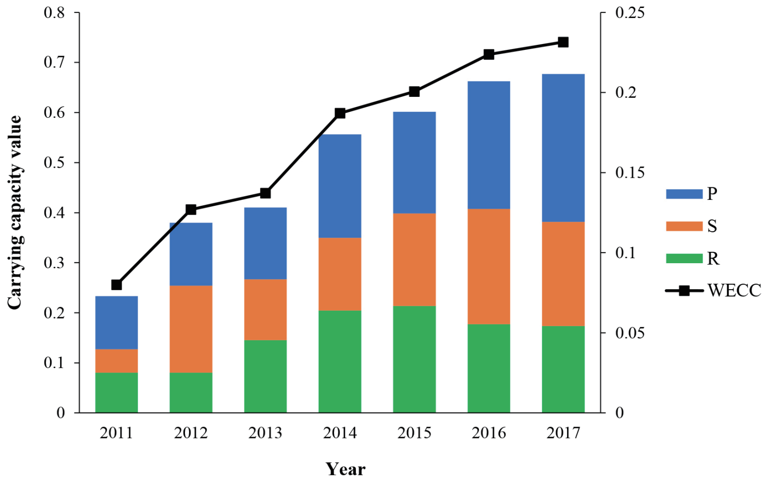


Fig. 6. (Color online) Changing trends of subsystem carrying capacity.

understanding of the interactions among influential factors and facilitated better decision making. Ningbo's pressure subsystem showed a continuous upward trend, and the water eco-environmental state and environmental protection response showed a slightly fluctuating increase. In Ningbo, over the past years, active measures with various degrees of success have been applied, particularly in terms of water environment pressure. The water eco-environmental state and environmental protection response are key factors for improving Ningbo's WECC in the future.

6. Conclusion

WECC is a complex concept. The current research on WECC insufficiently reflects its internal and external information, which leads to the incomplete identification of water environment problems, and it is difficult to provide system support for water environmental protection. Among the evaluation indices of various subsystems, we found that the improvement of WECC was attributed to the decrease in water consumption in the pressure subsystem and the improvement of water quality in the state subsystem through the analysis of the normalized values. Managers need to continue the struggle in this field and achieve industrial water conservation by adjusting water conservation measures within industries and improving the reuse rate of industrial water.

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